Advanced Telescope and Observatory (ATO)

Capability Cost Estimate

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Table: Capability Cost Estimates

Capability Title	Major Milestone(s)	ROM Five-Year Cost (FY06 – FY10)	ROM Run-out Cost	Notes
Low-Cost Cryogenic Optics	4 meter cryogenic mirror	$ 3-10 M	$ 30-60 M	For TPF-I, SAFIR & LF
	polarization mirror	$ 0-3 M	$ 3-10 M	For IP
	> 10 meter segmented cryogenic mirror	$ 3-10 M	$ 10-30 M	For SAFIR & LF
Low-Cost Precision Optics	1.8 meter precision mirror	$ 10-30 M	$ 10-30 M	For TPF-C
	4x8 meter precision mirror	$ 10-30 M	$ 100-300 M	For TPF-C
	10 meter segmented UVO mirror	$ 3-10 M	$ 30-60 M	For LUVO & PI
	Low Cost 3-meter Replicated Mirrors	$10-30M	$30-60M	For Low Cost 3-m telescopes for Earth Science, Midex/Discovery, Other Govt Agencies
Low-Cost X-Ray Optics	1 meter 15 arc-second x-ray mirror	$ 10-30 M	$ 60-100 M	For Con-X
Active Control WFSC Control	10hz active control of a segmented system	$30-60M	$60-100M	For Low cost 3-meter class telescopes, LUVO, TPFC, LF, PI
High Precision Metrology		$10-30M	$30-60M	For LISA
Speckle Sensing and Control	10e10 broadband contrast	$30-60M	$60-100M	For TPFC
Precision Path Control	Picometer control	$3-10M	$30-60M	For TPFI, SPECS, SPIRIT
Disturbance Reduction System		$3-10M	$30-60M	For LISA
Formation Flying		$10-30M	$100-300M	For GEC
Precision Formation Flying		$3-10M	$100-300M	For TPFI
Precision Structures-Stability and Isolation	8-meter class, low vibration structure	$3-10M	$30-60M	For TPFC
Precision Structures – Large and Cryo	10-m class, 4K Structure	$3-10M	$30-60M	For SAFIR
4-10K Active Cooling	4K Active+Passive Cooling	$3-10M	$30-60M	For SAFIR, SPECS, SPIRIT

Large, High Performance Test Facility	New Facility		$60-100M	Funded through other means

Low-Cost Cryogenic Optics

Low-cost cryogenic optics is an enabling capability for several potential mid-term infrared, far-infrared, sub-millimeter and microwave missions, including: TPF-I (Terrestrial Planet Finder Interferometer), SAFIR (Single Aperture Far-IR) and IP (Inflation Probe). All these missions required 2 to 4 meter class, modest-quality mirrors and/or mirror segments which operate at temperatures from 4 to 40K. Current state of the art is 2 meter class cryogenic mirrors that, while they satisfy most of the technical requirements, their areal cost is too great. **The most important enabling capability is to reduce the areal cost of cryogenic mirrors by an order of magnitude.** Several approaches to achieve this goal include replication, nanolaminates, near-net shaping, new mirror materials and advanced polishing techniques.

This capability has three specific milestones that directly connect with specific planned NASA Roadmap missions:

> 4-meter class cryo-mirror – Terrestrial Planet Finder Interferometer (TPF-I) mission can be enhanced by a 4 meter cryogenic mirror capability. TPF-I could be accomplished with a segmented mirror composed of current state-of-art (SOA) 2 meter class segments, but a monolithic mirror is preferred. Doubling the SOA from 2 to 4 meter class mirrors also enhances potential SAFIR and LF missions.
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> Polarization mirror – Inflation Probe (IP) mission can be enabled by a uniform polarization preserving optical coating on a 4 meter class cryogenic mirror.
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> ≥ 10-meter class mirror – Single Aperture Far-IR (SAFIR) mission can be enabled by a 10 to 15 meter class segmented 4K primary mirror capability. The LF mission is also enhanced.

Basis for cost estimate are: 1) the Advanced Mirror System Demonstrator (AMSD) program which developed the flight mirror technology for the James Webb Space Telescope (JWST); 2) Spitzer, SOFIA and Hershel mirror fabrication experience; 3) multiple cryogenic mirror technology development SBIR projects; and 4) conversations with potential cryogenic mirror technology vendors.

Cryogenic Optics is a Capability for applications that are unique to the NASA Space Missions Directorate. There are very few if any commercial or other governmental agency applications for optics which operate from 4 to 40K. Thus, it is critical for NASA to lead the technology development of this Capability.

Low-Cost Precision Optics

Low-cost precision optics is an enabling capability for two potential mid-term extreme ultraviolet, ultraviolet and visible missions: TPF-C (Terrestrial Planet Finder Coronagraph) and LUVO (Large Ultra-Violet Observatory). Both missions require large-aperture extremely-smooth extremely-stable ambient temperature mirrors. It also enables several future 3-meter class telescopes. The cost-effective fabrication of 2 meter class segments and an 8 meter class monolithic mirror requires the application of precision optical fabrication and metrology techniques that have previously been demonstrated on only <0.5 meter class microlithography optics.

This capability has four specific milestones that directly connect with specific planned NASA Roadmap missions:

> 1.8-meter class precision-mirror – Large Ultra Violet Observatory (LUVO) is enabled by the capability to make 2 meter class precision mirrors. Additionally, this capability is a critical incremental step towards enabling 8 meter class mirrors required for TPF-C.
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> 4 x 8 meter monolithic mirror – Terrestrial Planet Finder Coronagraph (TPF-C) requires a primary mirror that has never before been demonstrated - an extremely smooth (4 nm rms surface figure) 4 by 8 meter monolithic lightweight (~40 kg/m2) mirror with extremely uniform optical coating reflectivity, polarization properties and thermal/mechanical stability.
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> 10-meter segmented UVO mirror – LUVO mission can be enabled by a 10 to 15 meter class segmented UV/O primary mirror capability. Key technologies include: capability to polish surface figures all the way to the edge of the segment; capability to sense and control relative segment edge positions to sub-nanometer precision; improved optical coating such as highly uniform high reflectivity coatings from 90 to 120 nm; and telescope structural stability.
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> Low Cost 3-meter mirrors – Could include replicated mirrors that can be made very low cost even if higher mass. Could enable many future 3-meter class telescopes for Midex/Discovery type budgets, LIDARS, Lasercomm receivers, etc. Could include nano-laminates and spherical casted glass mirrors.

Basis for cost estimate are: 1) the Advanced Mirror System Demonstrator (AMSD) program which developed the flight mirror technology for the James Webb Space Telescope (JWST); 2) HST and FUSE mirror fabrication experience; 3) multiple mirror technology development SBIR projects; and 4) conversations with potential precision mirror technology vendors.

Precision Optics for UV/Visible Telescopes is a Capability with multiple government and commercial applications. The Large Optics Working Group (LOWG) of the Space Technology Alliance (STA) tracks the activities of multiple government organizations and agencies in this technology area.

<u>Low-Cost X-Ray Optics</u>

Low-cost x-ray optics is an enabling capability for several potential x-ray and far-ultra-violet missions. The only mid-term mission is Constellation-X (ConX). The capability required to enable ConX is truly advanced when compared with Chandra. ConX plans a four spacecraft architecture soft x-ray observatory with 60X the effective collecting aperture as Chandra (6 square meters). Each telescope is planned to be 1.6 meter diameter x 1 meter long with 20X lower areal density (< 3 kg/m2) and 50X lower areal cost (< $ 0.1 M/m2). **The most important enabling capability is to reduce the areal cost and areal density of x-ray mirrors by two orders of magnitude.** Efforts are underway to develop new materials and fabrication processes.

This capability has one specific milestone that directly connects with a specific planned NASA Roadmap missions:

> <u>1 meter 15 arc-second x-ray mirror</u> – Constellation-X (ConX) mission is enabled by this Capability.

Basis for cost estimate are: 1) on-going development activities funded by the ConX program; 2) Chandra, XMM-Newton, Astro-E, SXI and Solar B mirror fabrication experience; 3) multiple x-ray mirror technology development SBIR projects; and 4) conversations with potential x-ray mirror technology vendors.

X-Ray Optics is a Capability for applications that are unique to the NASA Space Missions Directorate. There are very few if any commercial or other governmental agency applications for x-ray optics. Thus, it is critical for NASA to lead the technology development of this Capability.

<u>Active Control Wavefront Sensing and Control</u>

This capability includes the continuous sensing and control of segmented or interferometric mirrors over high temporal bandwidths (>10hz) and will be needed for a number of interferometric and segmented systems including TPFC, LISA, TPFI, LUVO, Life Finder, and Low Cost 3-meter telescopes. This includes developing fast image based algorithms, high speed flight and ground digital signal processors, optical metrology equipment (like corner cubes), fast laser trusses, and advanced algorithms and testbeds. This capability could enable whole new architectures of telescopes that can be used at L2, Lunar Telescopes, Earth Science Telescopes, laser comm. systems, LIDAR systems, and telescopes for other government agencies and therefore is a major investment area. Basis for estimate is ongoing LISA work and NRO, AFRL and NASA work on Low Cost 3-meter telescopes. The estimate also takes into account costs of other similar testbeds and previous technology development costs in this area.

<u>High Precision Metrology</u>

This capability includes very high precision laser-based metrology systems for use in gravity wave interferometers. The key need is for laser metrology gauges capable of repeatable measurements with picometer accuracies over extremely long distances. A major issue here is the needed accuracies must be stable over hours. Cost estimates account for current existing developments for LISA and accounts for additional improvements needed for LISA, BBO, and UV Optical Interferometers.

Speckle Sensing and Control

This capability includes speckle-suppression hardware and software to achieve the required 10^{10} contrast in broadband light. Improved fidelity in vector (polarization) optical modeling is needed to meet the accuracy requirements of high-contrast imaging. This capability also includes wavefront control for TPF-C which will require 50 picometer (pm) (λ/10,000) deformable mirrors stable over periods of hours or new architectures based on active control will need to be developed. TPF-C will also require innovative amplitude masks with unprecedented accuracy. Cost estimate accounts for current state of the art (10**9 monochromatic) and assumes previous and current limited levels of project funding by TPFC, the major stakeholder.

Precision Path Control

This capability is for precision path control of multiple collecting mirrors and/or beam combiners in either a segmented system or a formation flown or large boom type interferometer. This includes cryogenic precision motion control required for infrared systems. Closed-loop intelligent control of the entire system, involving multiple sensors and multiple structures, operating at a variety of temporal bandwidths, will be required. Among the users of this technology will be TPFI, SPECS, SPIRIT, UV Optical Interferometers.

Disturbance Reduction System

This capability is for the disturbance reduction system needed for LISA and BBO to assure that gravity fields to do not disturb the gravity measurements.

Formation Flying

This capability is to build the first rudimentary formation flying systems for Sun-Earth type missions where precision is not needed and where few (3-20) spacecraft are needed. The cost assumption considers the state-of-the-art and need dates for this capability.

Precision Formation Flying

This capability is for precision formation flying that is needed for several interferometric imaging systems. These systems will need centimeter type absolute control accuracies so wavefront sensing and control can maintain mirror alignments to much higher tolerances. These can be achieved through a number of methods and is the subject of European development for SMART which is assumed here to be a collaborative effort requiring funding.

Precision Structures – Stability and Isolation

This capability is for stiffer, more stable large structures that can enable more stable systems (like TPFC), larger interferometers and segmented telescopes.   The TPFC need will drive more thermally stable systems that will require new material improvements. Another key investigation area will be the use of nano materials such as carbon nanotubes for improved material properties. This area also includes isolation and dampening systems for lowering vibrations in a cost-effective manner that will be needed for more precise systems like LUVO. The cost estimate assumes state-of-the-art from JWST of a 6.5 meter structure with passive isolation.

<u>Precision Structures – Large and Cryo</u>

This capability includes larger cryogenic structures needed for missions beyond JWST such as SAFIR and SPIRIT. These systems need to cold to colder temperatures (4-10K instead of 30K) and need to be even larger (10-30-meter class). This will require additional deployment or assembly complexities that need to be developed. The cost estimate is based on similar developments for JWST.

<u>4-10K Active Cooling</u>

This includes a new capability of combining passive and active systems to achieve 4-10K telescope systems. Current state of the art is for passive systems (eg, JWST sunshade) or for active systems (eg, cryo-coolers). This development effort is to combine these into integrated systems capable of achieving lower temperatures and is based on previous costs for developing the passive and active systems separately.

<u>Large, High performance Test Facility</u>

This capability is for a follow on test facility to accommodate TPFC and SAFIR telescopes. The facility needs to accommodate at least a 10-meter diameter telescope, be able to support a helium cooling system to achieve 4K, and have extremely low vibrations. The assumptions here is the $60-100M run-out cost would not be part of a technology budget but funded through some other means when it becomes necessary.